Numerical Weather Prediction

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Forecasting Research Technical Report No. 426

R. Saunders, T. Roberts, A. O'Carroll and L. Horrocks

email: nwp_publications@metoffice.com

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R. Saunders, T. Roberts, A. O'Carroll and L. Horrocks

Satellite Applications, NWP,
Met Office, Fitzroy Rd.,
Exeter EX1 3PU, U.K.

Date	Version	Action/Comments	Approval
10/04/03	1.0	Draft for comment by authors	-
29/4/03	1.1	Revised after authors comments	
29/5/03	1.2	Further revision comments from N. Rayner	
16/11/03	1.3	Added AATSR	
13/1/04	1.4	Made corrections from reviewer J. Eyre	
23/1/04	1.5	Approval by JL1	R. Saunders

Comparison of ATSR/AATSR and TMI sea surface temperatures with the Hadley Centre analyses

by
R. Saunders, T. Roberts, A. O'Carroll and L. Horrocks

Abstract

A three way comparison has been performed of sea surface temperatures inferred from two Along Track Scanning Radiometers, (ATSR-2/AATSR) with those inferred from the Tropical Rainfall Monitoring Mission (TRMM) microwave imager (TMI) and the Hadley Centre sea-ice and SST analyses, HadISST1. The results showed there were more similarities between the ATSR-2/AATSR and TMI SSTs than with the HadISST1 analyses. For latitudes less than 40^{o}N ATSR-2/AATSR SSTs did not appear to be affected by undetected cloud contamination over the tropics and northern hemisphere but some cold biases were seen in the S. Hemisphere of up to 1.5 degK. The AATSR SSTs in 2003 were up to 0.2K warmer than HadISST1 whereas for the same months in 1998 the ATSR-2 SSTs were about 0.1K cooler than HadISST1. For the satellite comparisons with the HadISST1 analyses some differences are observed in regions of strong SST gradients, and a Pacific equatorial bias develops from May 1998 to January 1999, which is linked to a time-lag in the analyses of the dissipation of El Nino.

1. INTRODUCTION

Retrievals of sea surface temperature (SST) can be made from satellite sensor measurements in either the infrared or microwave regions of the electromagnetic spectrum, as atmospheric 'windows' exist in both. There are advantages and disadvantages of using either wavelength region for inferring SST, which are summarised below.

Infrared sensors make use of a combination of channels in the 3.7μm and 10-12μm wavelength atmospheric windows where the atmospheric transmittance is normally greater than 50% for most marine atmospheres. An advantage of sensing the sea surface in the infrared is that the field of view at the surface can be well defined and be as small as 1x1 km^2 allowing fine detail to be observed right up to coastal regions. However for climate model analyses this is not so critical as the model analysis grid is 1^{o} x 1^{o}. Other advantages are the sensors can be accurately calibrated with on-board black bodies and the multi-channel, multi-view approaches allow a robust retrieval to be developed which removes the influence of the intervening atmospheric absorption and scattering. Finally the emissivity of the sea surface at infrared wavelengths is close to unity so that any atmospheric reflected component is small.

The major disadvantage of remote sensing the surface at infrared wavelengths is that any clouds entering the field of view affect the measurements and so an effective cloud detection algorithm has to be employed. As more than 80% of the sea surface at any one time is covered by cloud this significantly reduces the coverage especially in meteorologically active areas. The coverage is less of a problem for climate datasets where monthly means are often used but if any undetected cloud is present it can cause a 'cool' bias in the retrieved SSTs, which is a potential source of error when inferring long-term climate change signals. Also some areas of the southern oceans are so persistently cloudy that the number of cloudfree infrared measurements are very limited over a month.

In contrast microwave measurements at frequencies below 20 GHz are insensitive to most types of cloud, with the exception of strongly precipitating cloud. This allows a more complete coverage to be made with no biases due to cloud if the rain affected data can be screened out. The main problem with microwave radiometers at these frequencies is that due to limitations of antenna size, the footprint size on the sea surface is around 50 km and close to coasts/islands the radiation in the side lobes of the antenna can contaminate the radiance measurements. This reduces the coverage in locations where there are many islands in the vicinity. Also the emissivity of the sea surface at microwave frequencies is lower and less well known than in the infrared.

To assess the errors of infrared and microwave SST retrievals and SST climate analyses a three-way comparison of SSTs computed from measurements of the Along Track Scanning Radiometers (ATSR-2 and AATSR) and the Tropical Rainfall Monitoring Mission (TRMM) microwave imager (TMI) were compared with the SST and sea-ice analyses from the Hadley Centre (HadISST1) for several months in 1998 and 2003. A description of the satellite data used is given in section 2 and of the HadISST1 SST analysis in section 3. The results of the comparison are presented in section 4 and summarised in section 5.

2. DESCRIPTION OF SATELLITE MEASUREMENTS

2.1 Along Track Scanning Radiometer measurements

The Along Track Scanning Radiometer (ATSR) has to date been flown on three satellite missions, ATSR-1 on ERS-1 (1991-1995), ATSR-2 on ERS-2 (1995-present) and the Advanced Along Track Scanning Radiometer, AATSR, on ENVISAT (2002-present). Each instrument has 3 infrared channels centred in the atmospheric windows at 3.7, 10.8 and 12.0 μm plus channels in the visible/near infrared part of the spectrum used for cloud detection. ATSR's unique feature is that it has an inclined conical scan which enables it to make observations of the surface from two different angles, nadir and a forward view (~55^{o}), within a few minutes of each other, allowing better correction for atmospheric absorption and aerosols. It also improves the cloud detection for some cloud types. Another important aspect of the ATSR design is the accurate calibration for the infrared channels through two on-board black bodies at temperatures above and below the SST range being measured. Finally the sensitivity of the detectors results in an instrument noise of less than 0.1 K allowing fine details to be observed in the retrieved SST images. This instrument design and the retrieval process leads to an absolute accuracy of less than 0.3K in the derived skin SST and a long-term stability of less than 0.1K. More details on the ATSR instrument design and performance in retrieving SST can be found in Edwards *et. al.* (1990), Mutlow *et.al.* (1999) and on the web at Mutlow *et.al.* (2000).

For this study only nighttime ATSR-2 and AATSR data were used which were coincident with microwave radiometer data (see below). There are several stages in processing the radiance data as measured by the radiometer. The top of atmosphere radiance data at 1km resolution is passed through a series of tests to identify cloud contamination (Zavody *et.al.;* 2000) and a 10 arc minute spatially averaged product of the clear sky radiances are stored to make up the consolidated averaged brightness temperature (CABT) product at Rutherford Appleton Laboratories (RAL). These spatially meaned radiances, hereafter referred to in units of degK (i.e. equivalent black body brightness temperatures), are archived at RAL. Currently the ATSR-2 mission from Jan 1995 to Jan 2001 is archived. The Met Office has access to this CABT archive and so any data required are copied to the processor in Satellite Applications for further processing to retrieve a skin SST (few microns in depth) from the top of atmosphere radiances. The skin SST is then converted into a bulk SST (1m depth) that can be compared with in-situ measurements and conventional SST analyses. The details of the (A)ATSR processing carried out at the Met Office are documented in Horrocks *et. al.* (2003a). For this study the bulk SSTs derived from the ATSR-2 radiances for several months in 1998 are used to compare with the other SST data sources. The ATSR-2 retrievals are from the RAL CABT data for dual view, 3-channel skin SSTs converted to bulk SST.

The AATSR retrievals are computed from the ESA meteo product provided in near real time to the Met Office in BUFR format (Envisat products handbook). These data have been received since 19 August 2002. Only the nighttime (A)ATSR data, with a correction for the cool skin (Horrocks *et. al.;* 2003b), are compared with TMI data to eliminate any uncertainties due to diurnal thermoclines in the (A)ATSR datasets.

The daily averaged (A)ATSR bulk SSTs for comparison with TMI and HadISST1 are formed by subtracting a 1 degree daily climatology from the 10 arc minute ATSR observations to create daily (A)ATSR SST anomalies. These anomalies are averaged into 1 degree cells. The daily anomaly fields are then used to create a monthly mean 1 degree resolution ATSR SST by combining all the daily anomalies, ignoring days with no data, and adding a monthly mean climatology at 1 degree resolution to the anomaly. Averaging the mean anomaly rather than the SST ensures the limited time sampling of (A)ATSR SSTs during the month does not produce unrepresentative monthly means.

2.2 TRMM Microwave Imager measurements

The Tropical Rainfall Monitoring Mission (TRMM) is a joint NASA and NASDA mission, which was launched in Nov 1997 and is still operating at the time of writing (2003). The TRMM orbit moves from west to east providing data at varying local times between latitudes of 40S and 40N. On board TRMM is the TRMM Microwave Imager (TMI), which is a conical scan microwave radiometer with channels at five separate frequencies: 10.7, 19.4, 21.3, 37 and 85.5 GHz and a spatial resolution of about 50km. The lowest frequency channel is used to retrieve SST as it is less sensitive to water vapour and cloud, so ocean with persistently cloudy coverage can be viewed more often than with infrared sensors.

However there are sensitivities to precipitation and sea surface roughness and so the microwave SST retrieval attempts to account for these effects. Details of the linear regression retrieval algorithm, which aims to derive SST to an accuracy better than 0.5 K, are given in Wentz and Meissner (2000). Briefly, a radiative transfer model and an ensemble of atmospheric profiles are used to model the effect of the atmospheric absorption (principally

water vapour) at 10.7, 19 and 37 GHz. The greater absorption at the higher frequencies allows a good estimate of the absorption at 10.7 GHz to be made. The sea surface roughness is inferred from the V&H polarisation ratio of measurements at the same frequency. Precipitation affected measurements cannot be used for SST retrievals and so the 37 GHz channel radiances are used to screen out these data. Microwave radiation penetrates to a depth of 1mm, so TMI retrievals are representative of a 'thick' skin temperature compared with the 'thin' skin temperature measured by ATSR. TMI comparisons with buoys give an rms difference of about 0.6 K some of which is due to the buoy and colocation errors (Wentz *et. al;* 2000) and some due to the skin-bulk SST difference for TMI (Gentemann *et. al.;* 2003).

The TMI SST product we have used is downloadable direct from the Remote Systems Website http://www.ssmi.com/ as daily, weekly and monthly averages and is available from December 1997 between -40 and +40 degrees latitude. We have used the daily averaged data processed with version 3a available from February 2003. These daily TMI means at a quarter of a degree spatial resolution are then averaged to one degree cells and compared with daily meaned ATSR SSTs at 1 degree resolution. An example of the monthly averaged TMI SST dataset for January 1998 is shown in Figure 1. In contrast to the (A)ATSR data all the data (i.e. day and night) is included in the monthly average as the diurnal effects will be less significant for TMI as it is in an orbit where the equator crossing times change. Also mainly cloudy data will be included in the monthly mean that will not have a marked diurnal cycle.

3. DESCRIPTION OF ANALYSES

The HadISST1 analyses produced by the Hadley Centre use both in situ sea surface observations and satellite (AVHRR) derived estimates of the bulk sea surface temperature. SSM/I data have been used to define the sea-ice edge. The sparse observations from ship tracks and buoys are taken and gaps are filled in using an EOF technique (Rayner *et. al.* 2003). It is a monthly mean global, 1^o x 1^o resolution dataset produced for the period from 1871 – 2003 but the AVHRR satellite data is only included after 1981. An example of the HadISST1 analyses for January and July 1998 are shown in Figure 2 where the cooling in the eastern tropical Pacific is clearly evident in July due to the breakdown of the El Nino. The analyses are used to validate coupled model simulations and to provide the lower boundary conditions for climate model runs.

4. RESULTS OF COMPARISONS

The period from January 1998 to December 1999 was chosen for the main comparison as ATSR-2 data, TMI data and HadISST1 analyses were all available at this time. In addition early 1998 was the peak of the El Nino in the tropical Pacific, which then died away later in 1998 and 1999. Secondly a period of 3 months in 2003 (i.e. Jan/Apr/Jul) was chosen in order to assess how AATSR SSTs compared with the TMI data and the HadISST1 analyses and to see if they had similar characteristics to ATSR-2 data. There are two main objectives in the three way comparisons, which are possible with these datasets. Firstly the (A)ATSR to TMI comparison is described to assess the effectiveness of the (A)ATSR cloud detection. Secondly the two satellite datasets are compared with HadISST1 in order to see if both independent satellite SST datasets show similar anomalies in the analyses.

4.1 ATSR-2 compared with TMI SSTs

The first objective of this study was to validate the accuracy of the ATSR-2 bulk SST product, in particular to assess if the cloud detection was eliminating all cloud affected radiances. Comparisons were made for January, April and July 1998. Figure 3 shows the differences between the bulk SST product from ATSR-2 and TMI for two of the months. The gaps in the ATSR-2 plots are where there are doubts in the quality of the data as indicated by flags in the CABT dataset provided by RAL.

The plots show a hemispheric variation in the difference with 'cold' ATSR-2 SSTs in the southern hemisphere and 'warm' ATSR-2 SSTs in the northern hemisphere for all three months. The positive difference in the N. Pacific suggests TMI SSTs are up to 2 K cooler than ATSR-2. Inadequate cloud detection in the infrared data would usually have led to the opposite signal. Comparisons of TMI SSTs with other datasets have also demonstrated a similar cool bias for TMI in the N. Pacific (C. Gentemann, personal communication). The results show the ATSR cloud detection is working well in most situations at latitudes north of 20^{o} S. Poleward of 20^{o} S the ATSR-2 data are cooler than the TMI SSTs by up to 1.5K which may indicate a problem due to residual cloud contamination although it is surprising it only manifests itself in the extratropical southern hemisphere and perhaps suggests a TMI zonal bias. The July 1998 comparison is similar to January except for the cool feature along the equator in the tropical Pacific related to the breakdown of the El Nino which suggests in regions of strong temperature gradients TMI averages the features more than ATSR-2 due to a less well defined footprint on the ocean surface. There is also an area south east of Yemen in the Arabian Sea where TMI is cool or ATSR-2 warm in the July plot by as much as 2K.

One of the additional parameters available with the ATSR-2 data is the number of pixels, which make up the 10 arc min average. If there was a problem with ATSR cloud detection it might be expected that the differences with TMI would be greater when there were fewer pixels in the average. Figure 4 shows the number of pixels for July 1998 in the ATSR-2 product. There are no obvious correlations with either the ATSR-2 differences with TMI (Fig 3) or HadISST1 (Fig 8).

4.2 AATSR compared with TMI SSTs

AATSR SSTs have also been compared to TMI during 2003, for the same months, January, April and July as the ATSR-2 comparisons were made in 1998. A similar hemispheric variation in the differences, as seen in the ATSR-2 results can be seen in Figure 5, where TMI is cooler than AATSR poleward of 20 degrees south. Figure 5 also shows that AATSR is warmer by up to 2 K in the Arabian Sea, also seen in the ATSR-2 -TMI plot (Figure 3) for July 1998. This feature is not seen in the other months analysed suggesting the differences are due to a seasonal effect.

In general for all 3 months analysed in 2003, AATSR is cooler than TMI in the Pacific poleward of 20S and warmer than TMI poleward of 20N. This characteristic matches that seen in the ATSR-2 comparisons, which may suggest a persistent bias in the TMI SSTs in these locations or cloud contamination in the AATSR data over the Southern Oceans.

4.3 ATSR-2 and TMI comparisons with HadISST1

Comparisons between the predecessor to HadISST1 (GISST) and the ATSR-2 ASST product generated by RAL and then corrected for the cool skin effect have already been reported by O'Carroll *et.al.* (2001) and with HadISST1 by Horrocks *et. al.* (2001). Both studies showed

the differences were small but on average ATSR-2 SSTs were about 0.1K cooler than the HadISST1/GISST datasets. The new statistics for the three months studied here are summarised in Table 1 and also show ATSR-2 is slightly cooler than the analyses by on average 0.1K. TMI has a small warm bias (~0.05K) relative to HadISST1 but larger standard deviations by typically 0.1K which represents a significant increase in error compared with (A)ATSR. The larger standard deviation in July for the global (A)ATSR SSTs may be related to larger differences over the N. Hemisphere high latitude oceans where HadISST1 and/or the satellite data can have larger errors.

Figure 6 shows the ATSR-HadISST1 differences and the TMI-HadISST1 differences for January 1998. There are both similarities and differences in the two plots. In the latitude band 0-20S both satellite datasets suggest HadISST1 is 0.5-1 K cool. Also the analysis has a cool tongue of water across the Indian Ocean from equatorial Africa to southwestern Australia. In contrast, in some areas of the S. Pacific (west of S. America) and S. Atlantic (west of S. Africa) the satellite data are cool by up to 1 K. These are related to areas of persistent stratocumulus.

There is also a striking difference in the plots for the N. Pacific where the ATSR-2 data show HadISST1 to be unbiased but the TMI data suggest it is too warm by up to 2 K. This is also seen in Figure 3 where the two satellite products are compared. One cannot be certain but it seems more likely the ATSR product is closer to the truth in this case.

Finally some regions of the southern oceans not covered by TMI suggest the ATSR-2 SSTs have a cool bias of 1-2K which could be attributed to cloud contamination but with no TMI data this is difficult to confirm.

The corresponding plots for April 1998 and July 1998 are shown in Figures 7 and 8. For April the difference plots show clearly 2 areas where the HadISST1 analysis is up to 4 K cooler than both sets of satellite data. They are the Gulf Stream just off the eastern seaboard of the U.S. and a long tongue of water stretching to the east of S. Africa (barely visible in the TMI plot). In addition there are both warm and cool areas to the west and east of Japan seen in the ATSR difference plot but not all the features are seen by the TMI plot. These are all areas where there are marked horizontal gradients in the SST field (see Figure 2) and so it is likely the analysis has slightly misplaced the exact location of the sharp gradient during this season when the SSTs are changing more rapidly.

The July 1998 data (Figure 8) also shows the analysis to be too cool in the same areas and in this case the Sea of Okhotsk, Caspian Sea and Hudson Bay also show up in the ATSR difference plot as areas where the analysis is cool by up to 5K. As for January, and to a lesser extent April, the TMI data appears to be cooler than both ATSR-2 and the analysis in the N. Pacific. A narrow band of warm ATSR-2 SSTs can be seen in the Northern Pacific to the south of a persistently cloudy area. It is unclear if this is an anomaly in the satellite data or the analyses.

There is a marked strip of anomalously warm water in the analysis along the eastern equatorial Pacific clearly evident in both ATSR and TMI plots and just visible in the April plots. This is related to the breakdown of the El Nino and it suggests the cooling of the surface layers in the eastern tropical Pacific, which is evident in Figure 2, is underestimated in HadISST1 by up to 3K. Figure 9 shows the time evolution of the TMI – HadISST1 SST differences for the eastern tropical Pacific between 10S to 10N from January 1998 to December 1999. From April 1998 as the El Nino starts to breakdown it is clear there is a narrow strip along the equator where HadISST1 overestimates the SST by 1-2 K for up to a year later. There is also evidence the tropical Pacific is not well represented from August

1999 onwards. In addition, to the north of the strip where HadISST1 is overestimating the SST, there is a narrow band where HadISST1 underestimates the SST by up to 2K probably related to a slight mis-location of the El Nino. This is more evident in the TMI data than the ATSR-2 data.

4.4 AATSR and TMI comparisons with HadISST1

Comparisons between AATSR and HadISST1 for January, April and July 2003 show in general fairly uniform differences between –0.3K to +0.3K. However, there are some features exceeding these limits to note. In all 3 months, the AATSR SSTs are warmer than HadISST1 by more than 2K in the region of the Southern Ocean just beyond South Africa. This feature is coupled with a strip of cooler AATSR SSTs just south of this location. The warm band of AATSR SSTs in this region correlates with a warm feature seen in the AATSR minus TMI comparisons. This feature is most marked in April (not shown). For July 2003 the plot shows that the Sea of Okhotsk is still 3-4K cool in the analysis but the Caspian Sea is closer to the AATSR values than in July 1998. The Hudson Bay still appears >3K cool relative to AATSR.

The TMI minus HadISST1 plots for January, April and July 2003 show features where TMI is warmer than HadISST1 in the northern hemisphere and cooler than HadISST1 in the southern hemisphere, but the locations of the maxima of these differences vary from month to month. The hemispheric variation is therefore perhaps a characteristic of TMI SSTs, as a similar pattern is observed with the AATSR minus TMI SSTs. For January 2003 the TMI minus HadISST1 plot (not shown) has north/south hemispheric features, which can have differences of greater than ±2K in the Pacific. These features do correspond with smaller differences, but in the same area, for the AATSR minus HadiSST1 plot for January 2003. The north Pacific has large areas where there are cooler AATSR and TMI SSTs than HadISST1.

Table 2 presents the statistics for the AATSR TMI and HadISST1 comparisons. Whereas ATSR-2 SSTs were marginally cooler than TMI (Table 1), AATSR SSTs were very similar to TMI. It is difficult to conclude anything from this variability, as the data coverage is very different for 1998 and 2003, and could cause this scale of discrepancy. Against HadISST1 the mean bias of AATSR is +0.2K, while for ATSR-2 it was –0.1K. While sampling differences may still have some impact in these comparisons, these global statistics indicate a potential mean global bias of up to 0.3 K between AATSR and ATSR-2 SST retrievals (the exact magnitude would require confirmation in direct ATSR-2 to AATSR cross-validation). Mean biases of a few tenths of K may be expected in infrared retrievals of SST since the radiative transfer modelling used to provide retrieval coefficients is accurate only to order ~0.1 K (Merchant and Le Borgne, 2004). Further systematic errors in retrievals of SST are also possible, a consequence of both variability in real atmospheric profiles, and the representation of a slightly non-linear relationship by a linear retrieval equation (Merchant et al., 2004). It will be possible to define an offset to apply to retrieved AATSR SSTs to align them with empirical data (e.g., buoys, HadISST1). The variances of the differences are similar for ATSR-2 and AATSR suggesting the retrievals have similar error characteristics.

5. SUMMARY

A three way comparison of HadISST1 SST analyses, ATSR-2/AATSR infrared SSTs and TMI microwave SSTs allows a meaningful assessment to be made of the HadISST1 analyses for 1998 – 1999 and 2003 over the tropical and sub-tropical oceans. It also allows an

assessment of any biases in the two satellite datasets. Several conclusions can be drawn from these comparisons.

i. The absolute bias in the ATSR-2 CABT product relative to HadISST1 is ~ –0.1K, which is within the uncertainties of the SST retrieval. The corresponding bias for the AATSR meteo product SSTs is +0.2K. These biases can be removed, if desired, by comparison with buoys. The standard deviation of the retrievals for both ATSR-2 and AATSR relative to HadISST1 are similar indicating they have a similar accuracy.

ii. The (A)ATSR SSTs are not significantly degraded by cloud contamination in the tropics and N. Hemisphere but cool biases south of 20^{o}S are seen where they are cooler than TMI by up to 1.5K. There is still uncertainty over cool biases in the (A)ATSR data poleward of 40^{o}S as TMI does not extend far enough to verify the (A)ATSR products in this area.

iii. The TMI SSTs compare well with the (A)ATSR SSTs in the tropics but are up to 2K cooler over the N. Pacific.

iv. The two satellite SST datasets in general agree better with each other than the HadISST1 analyses.

v. Regions with strong horizontal SST gradients can often be slightly misplaced in HadISST1 especially when the SSTs are changing rapidly. Also data sparse regions such as the Caspian Sea, Hudson Bay and Sea of Okhotsk can be more than 5 K in error in the analyses. These differences would be reduced if ATSR SSTs were assimilated into the analyses.

vi. One reason for the HadISST1 differences with satellite data is partly due to the lower spatial resolution of the HadISST1 analyses (2 degrees at this time).

vii. HadISST1 does not accurately represent the timing of the dissipation of the 1998 El Nino within 5 degrees latitude of the equator. Monthly mean differences in SST of 2 K are observed consistently for up to a year. Both the TMI and ATSR-2 data confirm this difference.

In 2002 a new microwave sensor was launched on Aqua to expand the scope of comparisons with HadISST1. The Advanced Microwave Scanning Radiometer (AMSR-E) on board Aqua now allows global coverage of microwave SST observations in contrast to TMI which was limited to the low latitudes. SST datasets from AMSR-E and AATSR will allow a more comprehensive inter-comparison, to that described here, to be carried out in the near future.

6. ACKNOWLEDGEMENTS

This work was carried out in support of the Climate Prediction Programme under the DEFRA funded contract to the Hadley Centre. Rutherford Appleton Laboratories are acknowledged for providing the ATSR-2 CABT dataset and Nick Rayner (Met Office) for providing the HadISST1 analyses. ESA are acknowledged for providing the AATSR in near real time. Remote Sensing Systems are acknowledged for providing the TMI SST retrievals who are sponsored by NASA's Earth Science Information Partnerships (ESIP): a federation of information sites for Earth Science; and by NASA's TRMM science team.

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	January 1998	April 1998	July 1998
ATSR-2 – TMI (only ±40 deg)			
Mean (K)	**-0.14**	**-0.02**	**-0.14**
St. Dev (K)	**0.65**	**0.61**	**0.60**
ATSR-2 - HadISST1 (global)			
Mean (K)	**-0.10**	**-0.08**	**-0.14**
St. Dev. (K)	**0.64**	**0.65**	**0.86**
TMI - HadISST1 (only ±40 deg)			
Mean (K)	**0.08**	**0.01**	**0.05**
St. Dev (K)	**0.68**	**0.69**	**0.71**

Table 1 Global mean bulk SST differences for ATSR-2 and TMI minus HadISST1 (nightime only)

	January 2003	April 2003	July 2003
AATSR - TMI (only ±40 deg)			
Mean (K)	**0.00**	**0.08**	**0.00**
St. Dev (K)	**0.61**	**0.57**	**0.54**
AATSR - HadISST1 (global)			
Mean (K)	**0.14**	**0.22**	**0.20**
St. Dev. (K)	**0.72**	**0.69**	**0.75**
TMI - HadISST1 (only ±40 deg)			
Mean (K)	**0.13**	**0.14**	**0.19**
St. Dev (K)	**0.81**	**0.76**	**0.73**

Table 2 Global mean bulk SST differences for AATSR and TMI minus HadISST1 (nightime only)

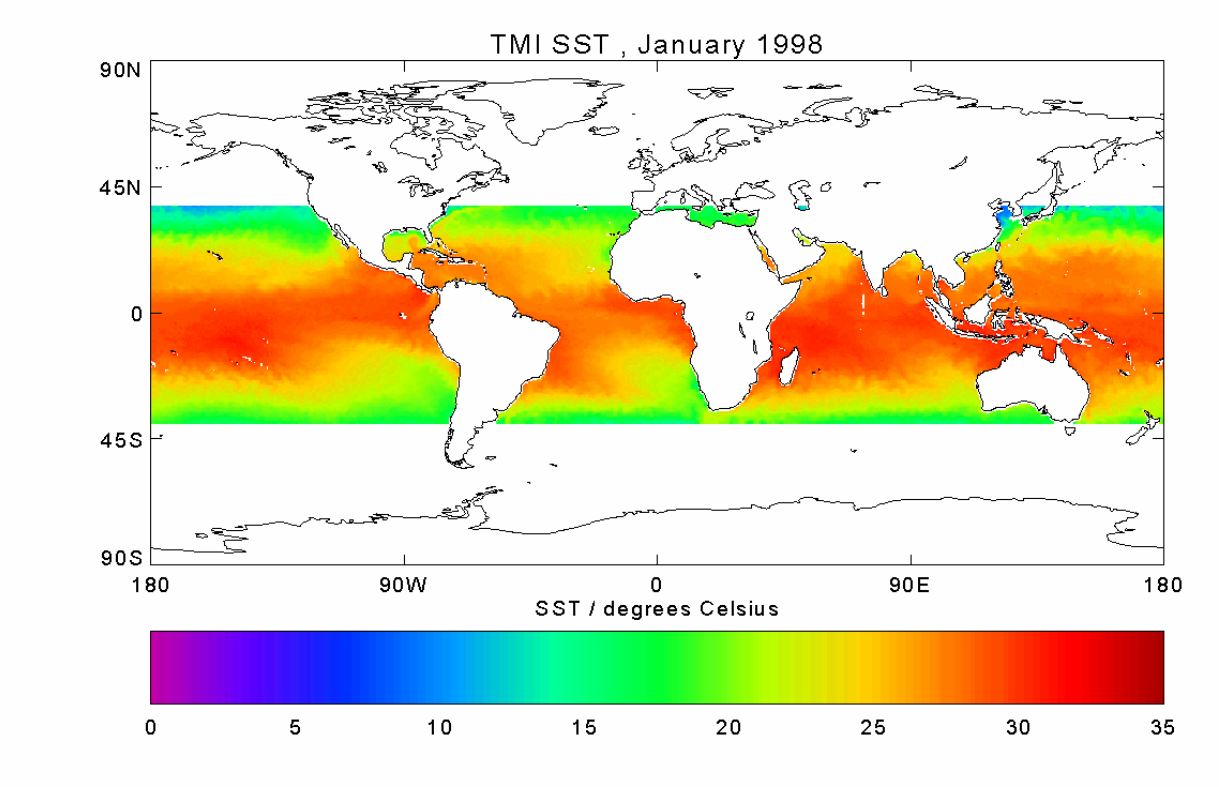

Figure 1: Example of monthly mean TMI sea surface temperature product for Jan 1998.

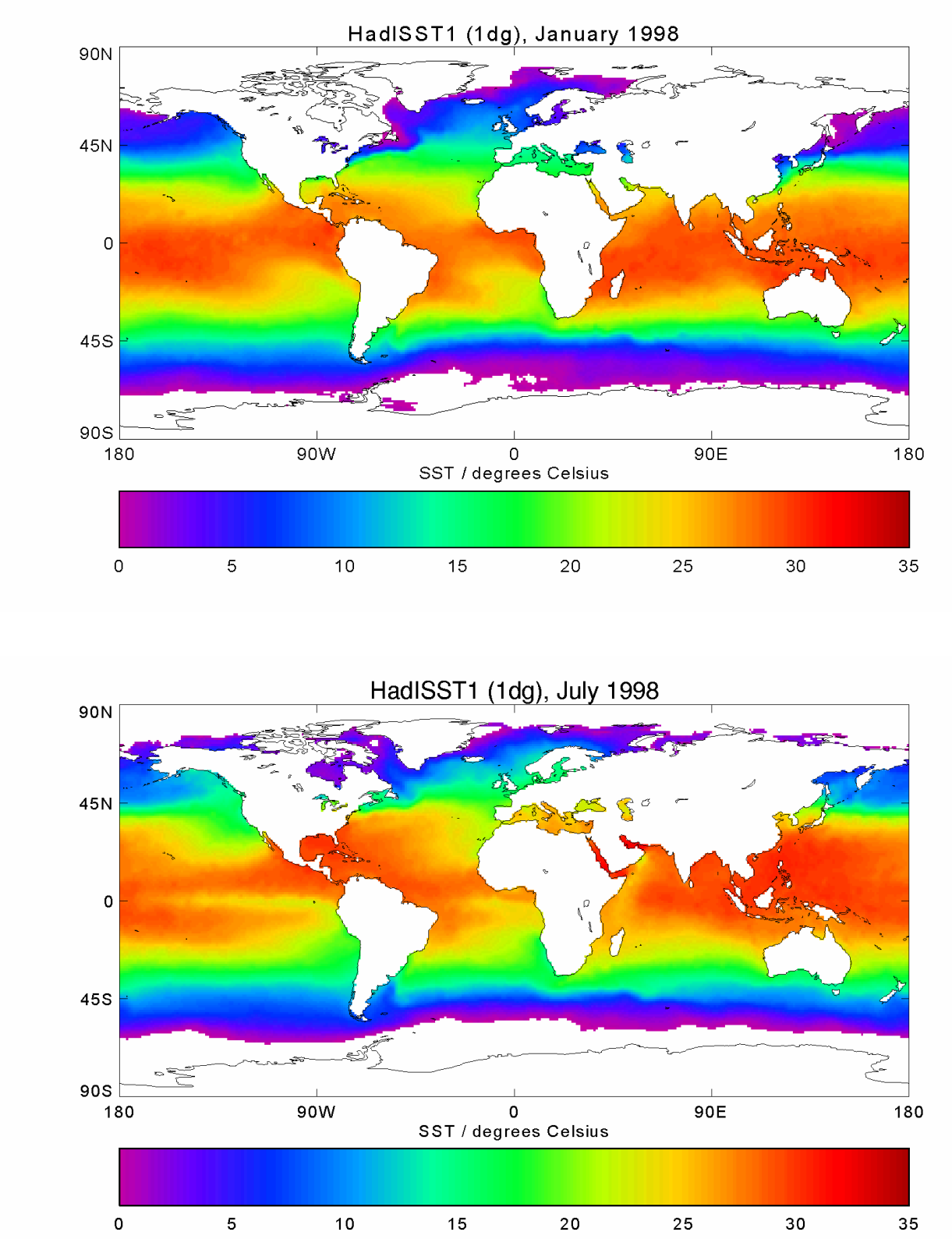

Figure 2: The HadISST1 monthly mean SST analyses for January and July 1998

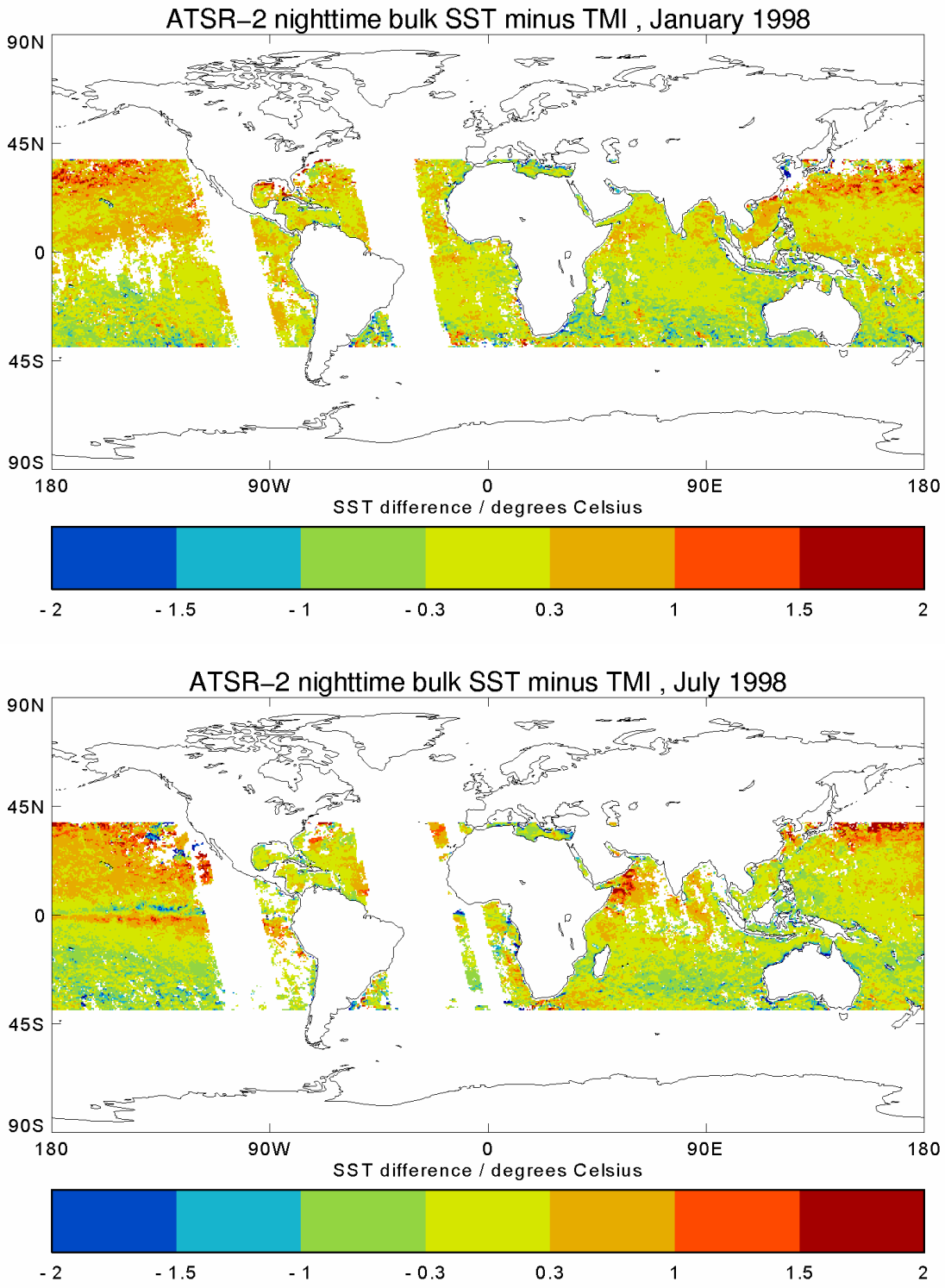

Figure 3: The difference between the nighttime ATSR-2 bulk SST and TMI SST for the months of Jan 1998 and July 1998.

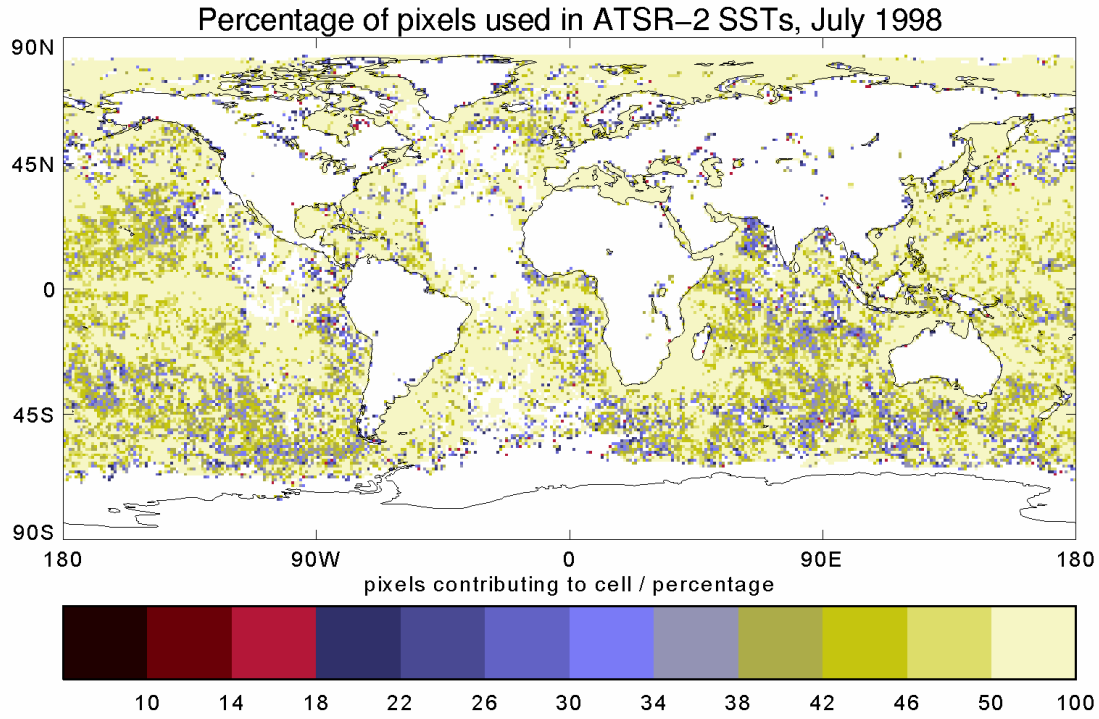

Figure 4. The number of cloudfree ATSR-2 pixels that make up a 10 arc min cell average for July 1998.

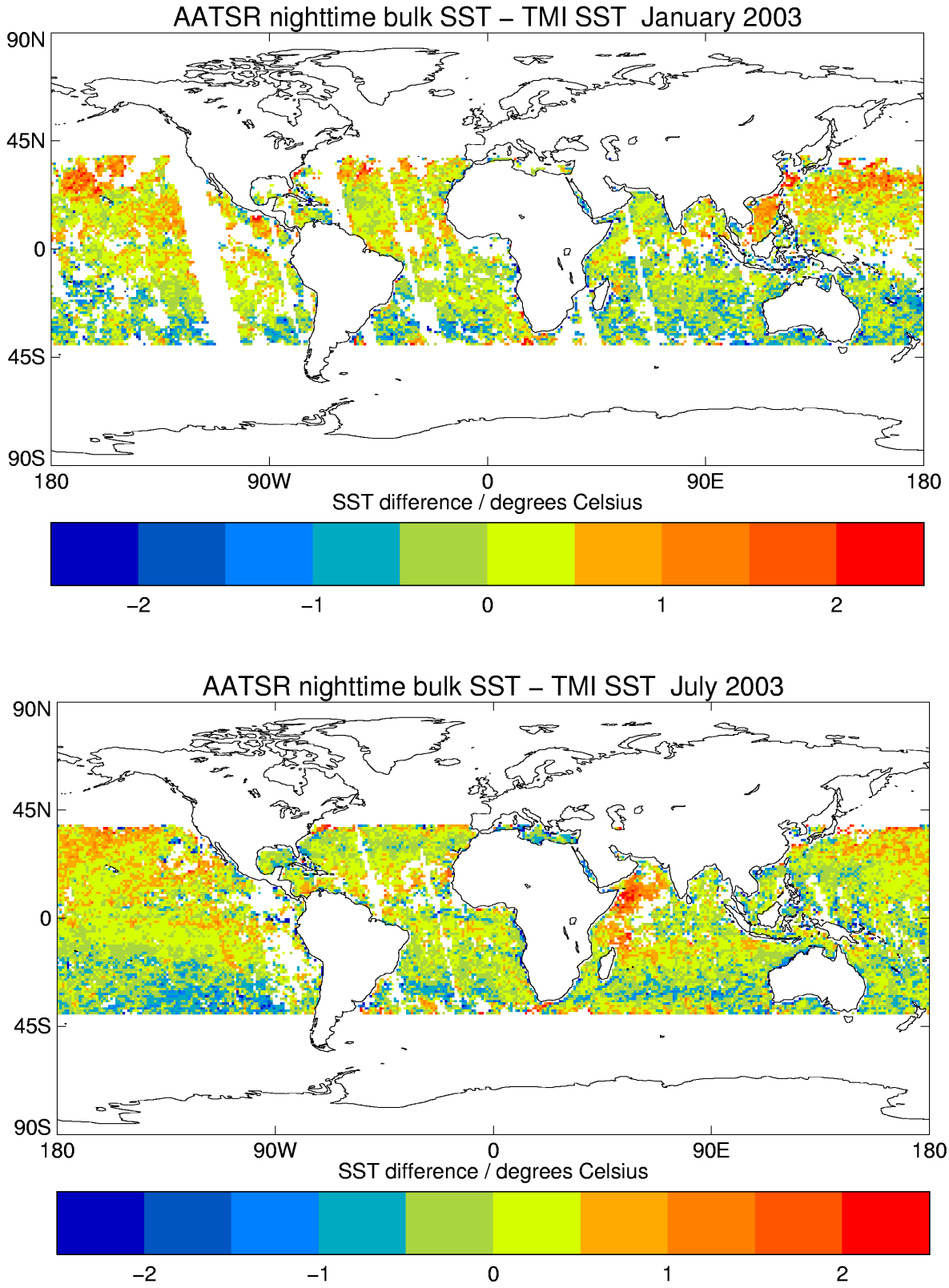

Figure 5: The difference between the nighttime AATSR bulk SST and TMI SST for the months of Jan 2003 and July 2003

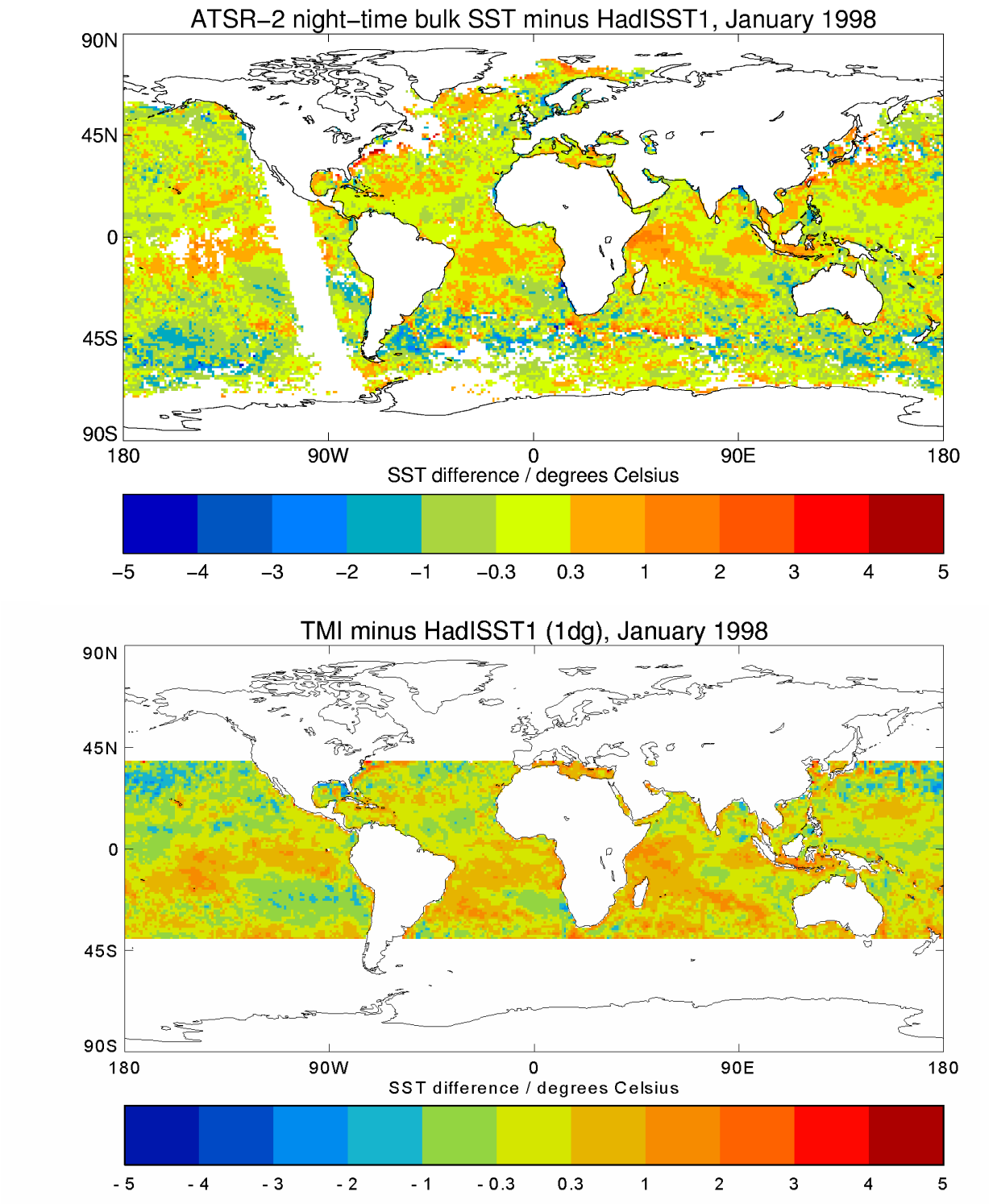

Figure 6: SST differences for ATSR-2 - HadISST1(upper) and TMI – HadISST1(lower) for January 1998.

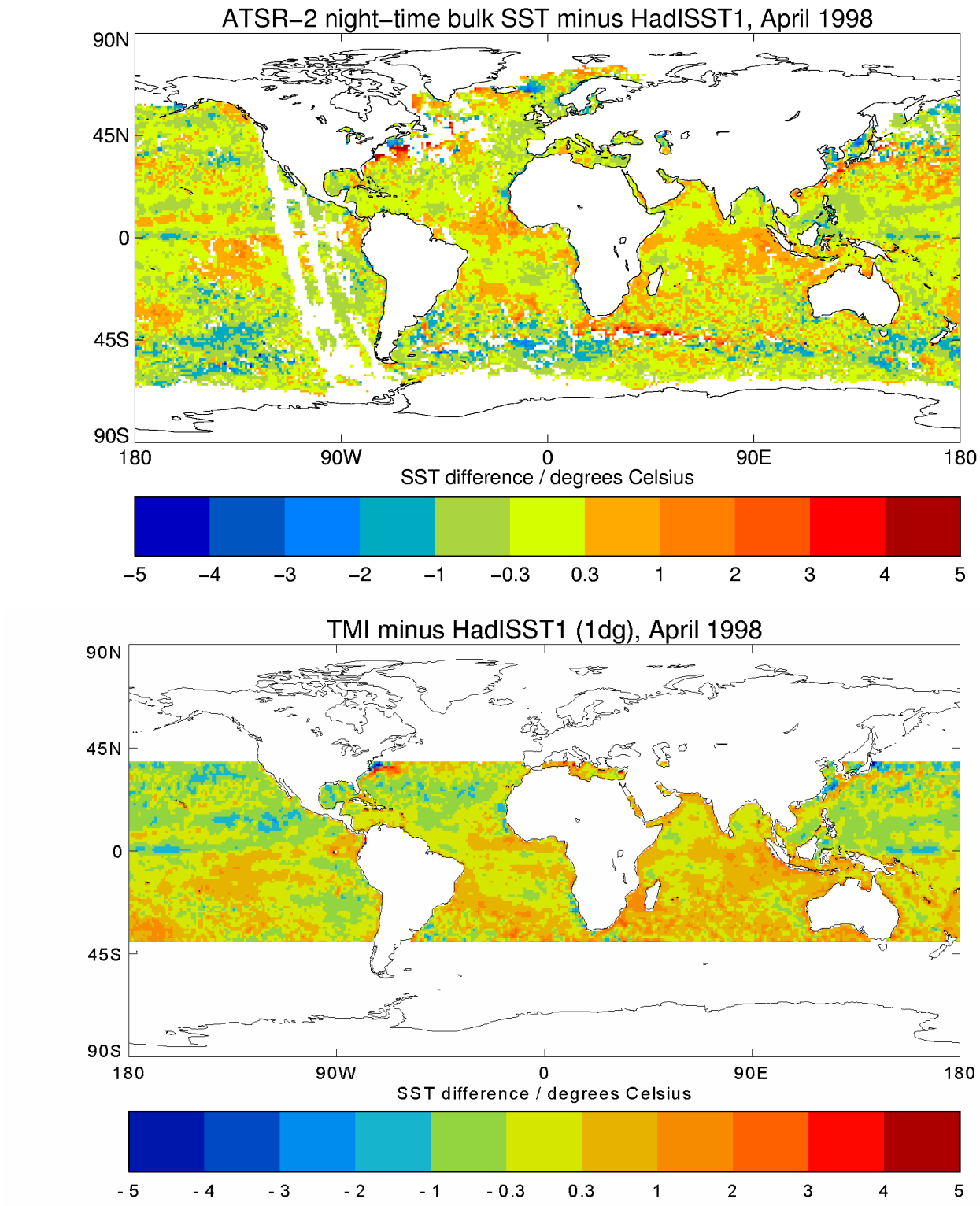

Figure 7: SST differences for ATSR-2 - HadISST1 (upper) and TMI – HadISST1(lower) for April 1998.

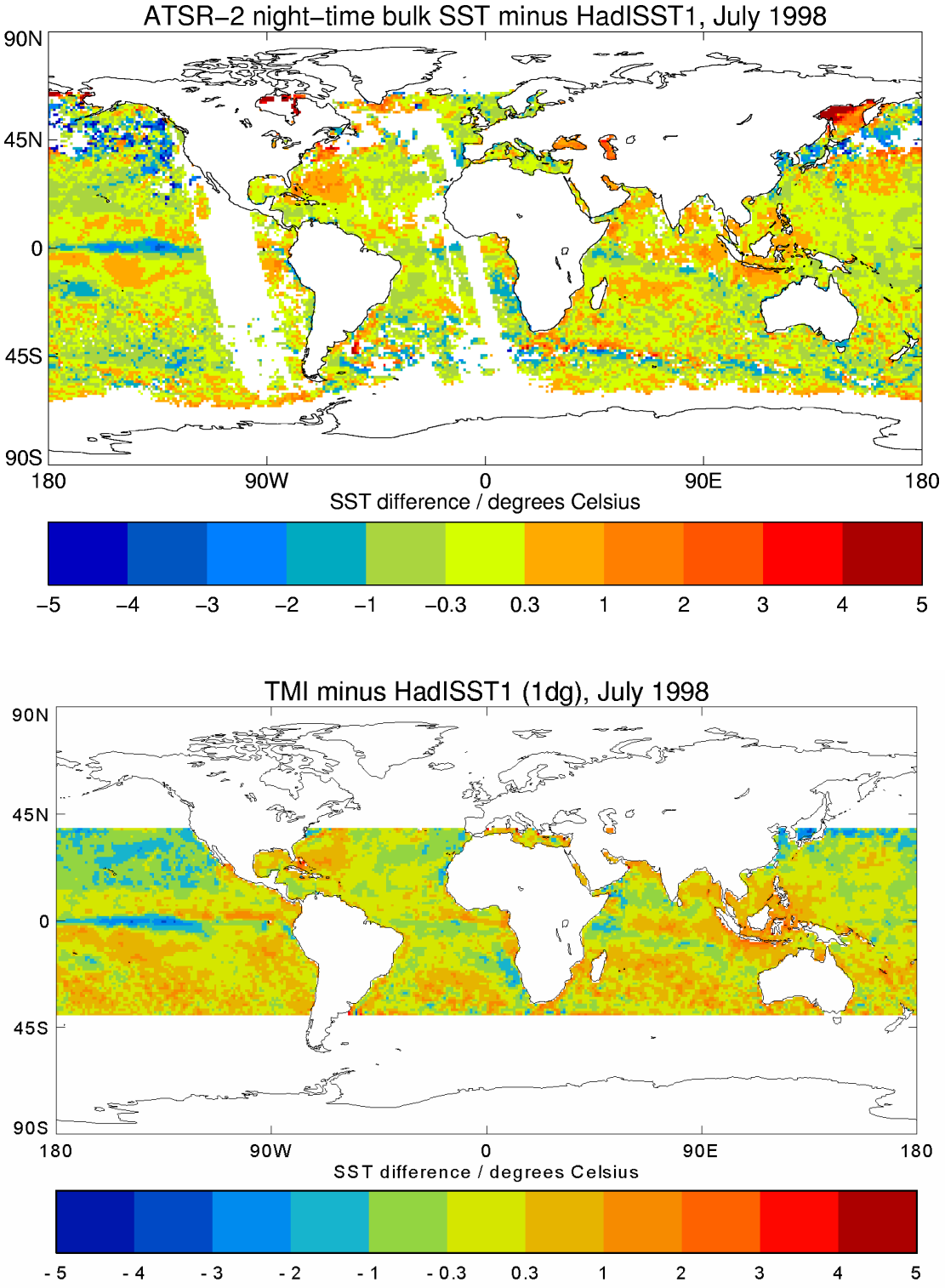

Figure 8: SST differences for ATSR-2 - HadISST1(upper) and TMI – HadISST1(lower) for July 1998

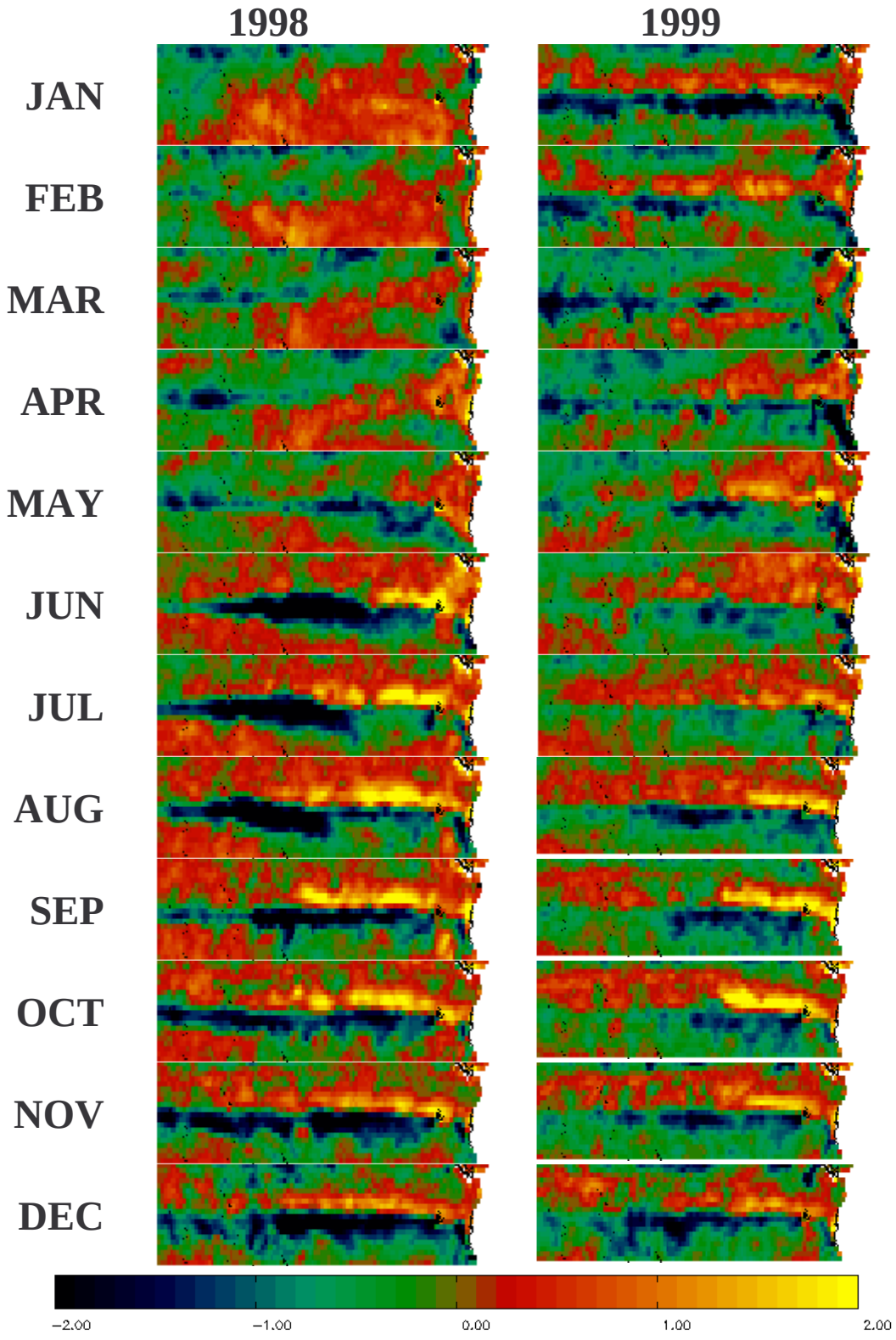

Figure 9. A time series of monthly mean TMI minus HADISST1 SSTs in degC for 1998 and 1999. The area plotted is of the tropical Pacific from 180W-80W and 10S to 10N.

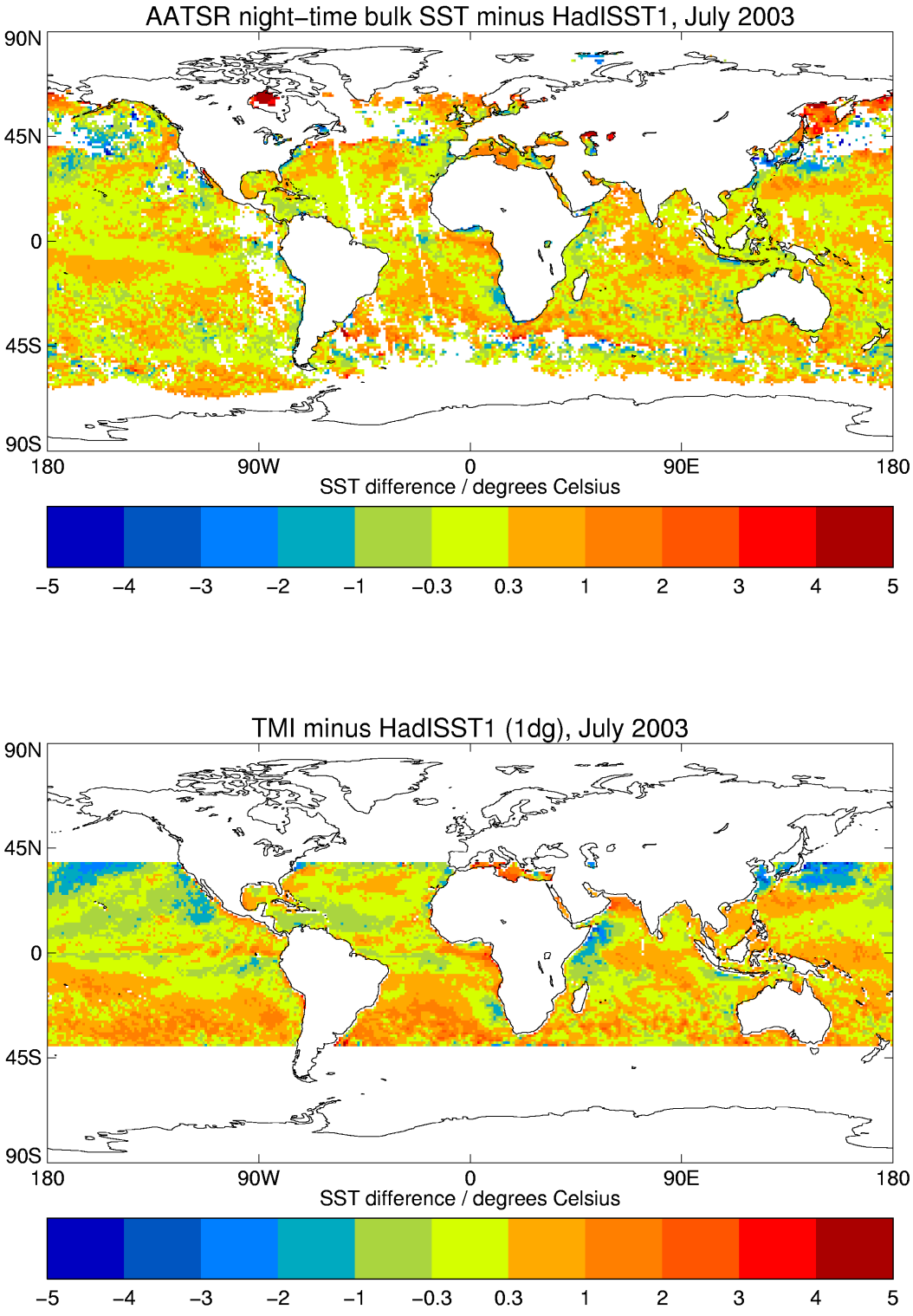

Figure 10: SST differences for AATSR - HadISST1(upper) and TMI – HadISST1(lower) for July 2003